Preliminary investigation of catchment hydrology in response to agricultural water use innovations: a case study of the Potshini catchment-S. Africa

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Abstract

Water use system innovations encompass various techniques for storing and conserving water resources in different mediums for domestic and livestock use including agricultural production. Such innovations for agricultural production are intended to conserve and preserve sufficient soil moisture in the root zone for crop uptake during the transpiration process, by encouraging infiltration and also by storing surface runoff for supplemental irrigation during dry spells. The rationale of adapting and adopting these water use system innovations is that, though seasonal amounts of rainfall (monthly, annual) may perceived to be adequate for crop production, its temporal distribution is poor in most of sub-Saharan countries and hence soil moisture deficits occur during crucial stages of crop growth. Careful management of moisture in the root zone provides opportunities to mitigate periods of soil water stress in the crop growing cycle. Although, several authors have indicated that rainwater harvesting techniques, especially for upgrading smallholder farming systems, are not new but have been practiced since ancient civilizations, the impacts of such water use innovations on eco-hydrological systems are rarely assessed, especially from a cascading spatial and temporal perspective. The need to quantify the supposedly potential and related hydrological impacts of water use innovations on a catchment and river basin at large led to the on-going research study aimed at investigating the biophysical consequences at different spatial and temporal scales in the Thukela river basin, of increased productivity in rainfed agriculture enabled through adoption at larger spatial scale of integrated land use management and water use system innovations. In this paper we discuss and outline of the approach used in setting up the research study in one of the catchments in the Thukela river basin, the the Potshini catchment, in the KwaZulu-Natal Province of S. Africa in an effort to seek answers to on the question: "What is the impact of adapting water use innovations in a predominantly agricultural area on catchment ecology and hydrology?" The approach incorporates a catchment monitoring network, hydrological modelling and application of a remote sensing technique, the Surface Energy Algorithm for Land (SEBAL), for spatially estimating the actual evapotranspiration and relative root zone soil moisture content in the region covering the Potshini catchment and beyond. It is envisaged that at, on accomplishment, the study will contribute to formulation of sustainable adaptation of water use innovations and up-scaling strategies to enhance food production and hydro-ecological balance in semi-arid savannahs of Africa, at which stage hydrological modelling will form an important part of the study.

Key words

Water use innovations, smallholder farming, rainfed agriculture, remote sensing, SEBAL

1.0 Introduction

The hydrological response of a catchment, as used in this context, can generally be defined as the reaction of a catchment to rainfall. Every catchment has a specific response to rainfall and which is related to hydro-climatological and physical characteristics, such as soil parameters, slope, climate etc. Some of the catchment characteristics can be obtained through measurements at specified spatial and temporal scales depending on their frequency and nature of occurrence and required resolution of data for meaningful analytical work when addressing questions related to catchment response. There are several factors that may influence a catchment response and can broadly be identified with change in land use/cover and climatic change. The influence or impact of climate change to catchment hydrology may not be depicted within a short term, as emerging trends of climatic parameters may indicate randomness rather than systematic pattern as compared to land use change. It should be noted

that causes of climate change are often not localized as compared to landuse change and thus making it easier to monitor and investigate impacts of landuse changes on the hydrological regime of a catchment and possibly impacts of the same to the downstream ecosystems. This can be achieved through establishing a catchment monitoring network, a task that was accomplished at the Potshini catchment in the foothills of the Drakensberg Mountains under the ongoing research programme, the Smallholder Water System Innovations (SSI) at the University of KwaZulu-Natal. The SSI research programme has the general objective of assessing the extent to which water management in rainfed smallholder farming can assist in securing human livelihoods in semi-arid tropical Savannahs in sub-Saharan Africa, together with trying to analyse the downstream hydrological implications of upgrading rainfed agriculture through adoption and adaptation of water use innovations e.g rainwater harvesting. Figure 1.0 indicates an overview of the Thukela river basin and the Potshini catchment. The Potshini catchment monitoring network facilitates the monitoring of the main hydrological processes in the predominantly agricultural catchment whilst recognizing the existing heterogeneity in such a catchment. Heterogeneity exists at any scale under consideration and it is a great challenge to hydrologists and water resource managers to uniquely define and quantify various hydrological processes in a catchment and establish the link between such processes and scales, both spatial and temporal. Such a challenge is further convoluted by the existence of a link between variability of hydrological processes and heterogeneity of the catchment (Jewitt and Görgens, 2000). This paper highlights the design and implementation of the field data collection programme, the importance of involving the local community in the process and preliminary research finding from the Potshini catchment.

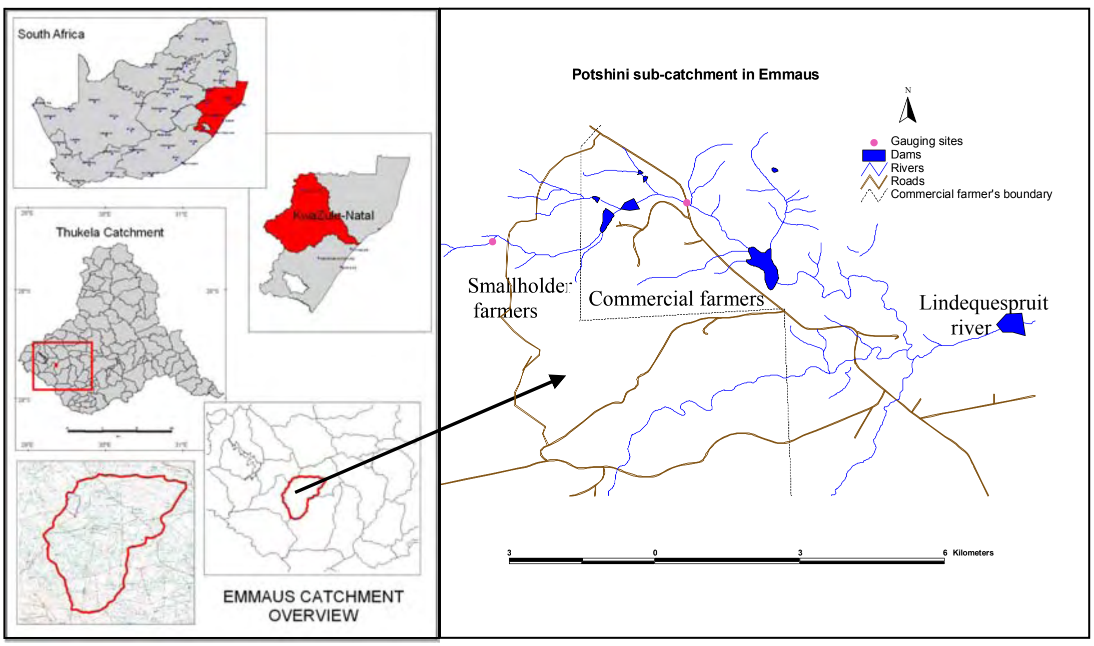

Figure 1. An overview of the Thukela river basin and the Potshini catchment

2.0 The Potshini Catchment

The Potshini catchment is predominantly a smallholder farming area and a sub-catchment of the Emmaus catchment in the Thukela river basin in the foothills of the Drakensberg Mountains in South Africa. Figure 1 shows the location of Thukela river basin together with the stream network at the Potshini catchment. The Thukela river basin has an area of 29,036 km^2, while the area of Emmaus catchment and Potshini sub-catchment are 280 and 1.2 km^2 respectively. The mean annual precipitation at Potshini is estimated to be 700 mm and the estimated mean annual potential evaporation is between 1600 to 2000 mm at an elevation of about 1250 meters above sea level (BEEH, 2003). Due to the hilly terrain, a good drainage network has developed in the Potshini catchment with most of the streams being perennial and providing water for domestic use to the upper part of the catchment, while replenishing reservoirs for commercial farmers downstream. Extreme low flows occur in winter (June to August). The main river, which drains the Emmaus catchment is the Lindequespruit, a tributary of the Little Thukela which later joins the Thukela river. The soils at the Potshini catchment are generally acidic with varying depths from 1.8m to over 3m on the lower parts of the catchment. Due to the need to intensify agricultural production in the area for food security, various agricultural management practices have been adapted in the Potshini catchment through the National Landcare programme in the Bergville

district, notably conservation agriculture (a water use innovation). There is a great potential for adoption of such practices in the area due to the successful results obtained so far where smallholder farmers have managed to increase their crop production per unit area by appreciable margins (Smith et al., 2004). The farmer-to-farmer participatory learning process, a participatory action research approach introduced in the area by the Agricultural Research Council (ARC), the implementing agency of the National Landcare programme in the Bergville district has been extremely successful in achieving the uptake of new techniques by the local farmers.

3.0 Water Use Innovations

According to Pandey et al., (2003), water use innovations are not new, but have persistently been developed and adopted by mankind as an adaptation to climate change since ancient civilizations. These innovations are either locally inspired or adapted from other regions. In the past few decades, efficient communication networks have greatly influenced and enabled technology transfer and hence adaptations of water use innovations in various regions of Africa. Water use innovations encompass various methods and strategies for mitigating drought in an effort to sustain livelihood. These innovations are water harvesting techniques for concentrating, storing and collecting surface runoff water in different mediums, for domestic or agricultural uses. Runoff can be collected from roofs or ground surfaces (rainwater harvesting) as well as from seasonal streams (flood water harvesting). The various methods for harvesting runoff can be distinguished after the following (Rockström, 2000):

- Source of the surface water (external or within-field catchments from sheet, rill, gully or stream flow)
- The method of managing the water (maximising infiltration in the soil, storing water in tanks/dams, inundating crop fields with storm floods) and
- The use of water (livestock, households, crop production and erosion management).

Water harvesting practices generally contribute to an increase in the recharge of water to the root zone and finally to the water table and operate at different scales (household, field, catchment and basin). Such practices have the potential to affect water availability and management for downstream water users and natural ecosystems due to reduced catchment water yields. Water harvesting for crop production, if successfully implemented within a social and hydrological catchment, will have many interacting implications on biophysical, economic, and ecological systems, suggesting that a systems approach be considered when promoting such innovations (Rockström, 2000). A systems approach would involve studies on different biophysical disciplines within a watershed and linkages between the agro-ecological system and rural society among others. It is important to understand these interactions and implications at different spatial and temporal scales before promotion and adoption of water use innovations in a catchment and river basin at large and it is the issue that this study aims to address.

Rockström (2000) cited SSSA (1987) as have defined conservation tillage as any tillage sequence having the objective to minimize the loss of soil and water, and having a operational threshold of leaving at least 30 percent mulch or crop residue cover on the surface throughout the year. Conservation tillage aims at reversing a persistent trend in farming systems of reduced infiltration due to compaction and crust formation and reduced water holding capacity due to oxidation of organic materials (due to excessive turning of the soil). From this perspective, conservation tillage qualify as a form of water harvesting (and hence a water use innovation), where runoff is impended and soil water is stored in the crop root zone (Rockström et al., 1999). Conservation tillage covers a range of non-inversion practices from zero-tillage to reduced tillage which aim to maximize soil infiltration and productivity, by minimizing water losses (evaporation and surface runoff) while conserving energy and labour. GHARP (2002) indicated the successes of conservation tillage in harnessing rainwater and improving yields (more than 50%) particularly in Machakos and Laikipia districts of Kenya.

3.1 Estimation of the "Green Water Flows" (Total Evaporation)

Increased levels of water resource management require increased accuracy in the quantification of various components of the hydrologic cycle especially the "Green" water flows (Falkenmark, 1995, Savenije, 1999,) i.e the gross return flo w of water to the atmosphere-total evaporation(evapotranspiration) in the form of water vapour, which includes a productive part as Transpiration (*T*) and a non-productive part as direct Evaporation (*E*) from the soil, lakes, and from the part of Precipitation (*R*) intercepted by canopy surfaces. According to Rockström (1999), in semi-arid tropical agriculture, direct Evaporation (*E*) generally accounts for 30-50% while transpiration (*T*) account for only 15-30% of total rainfall received. Evapotranspiration *(ET)* is highly variable over time and space and any effort towards enhancing the ability to confidently quantify it at large spatial scales is recognized as a key issue in water resources management. The challenge in determining the spatial and temporal variation of E_t over large areas is compounded by the many factors that influence its occurrence and prevalence and hence make it the most difficult parameter to determine in hydrology. The conventional approaches for quantifying *ET* has been based on localized point measurements which do not allow the flux estimation over large geographical areas. These approaches include direct measurements (evaporation pan, Lysimeters etc.), climatic stations (eddy correlations, Penman, Bowen ratio etc) and hydrological models (water balance). Remote sensing data provided by satellites are a means of obtaining consistent and frequent observation of spectral reflectance and emmitance of radiation of the land surface on micro and macro scale from which actual *ET* can be retrieved (Bastiaanssen et al., 1998). The main disadvantage of remote sensing approaches for estimating actual evapotranspiration is the limitation of accessing quality and timely data due to the influence of weather (cloud free images are required) and time overpass of satellite sensors, (Tasumi et al., 2003). One of the remote sensing approaches applied in this case study is the Surface Energy Balance Algorithm for Land (SEBAL), (Bastiaanssen et al., 1998 a&b, Bastiaanssen, 2000). SEBAL is an energy partitioning algorithm comprised of

twenty-five computational sub-models that calculate actual evapotranspiration and other energy exchanges at the earth's surface (Bastiaanssen, 1998a &b, 2000). The algorithm computes most essential hydro-meteorological parameters and requires limited ground based meteorological data (Farah and Bastiaanssen, 2001). Only incoming solar radiation, air temperature and wind speed data is required. SEBAL estimates actual evapotranspiration as the residual of an energy balance applied to the land surface for each pixel of the satellite image i.e

$$LE = R_n - H - G \tag{1}$$

where:
LE = is the latent heat flux ($W.m^{-2}$)
R_n = is the net radiation ($W.m^{-2}$)
H = is the sensible heat flux ($W.m^{-2}$)
G = is the soil heat flux ($W.m^{-2}$)

One of the intermediate outputs of the SEBAL algorithm is the sensible heat flux for each pixel of the satellite image and this gives an opportunity to calibrate the satellite image using measured sensible heat flux data obtainable from a Large Aperture Scinitillometer (LAS) as is will be applied in this study. The Large Aperture Scintillometer (LAS) is an instrument that measures the turbulent intensity of the refractive index fluctuations of air from the intensity fluctuations of a received signal (Cain et al., 2001). This signal is transmitted by a light source placed at a given distance apart (typically less than 10 km). At the receiver the spatial turbulent intensity is measured as a refractive index structure parameter C_n^2 ($m^{-2/3}$) which can be related to the structure function parameter of temperature C^2_T ($K^2.m^{-2/3}$). Additional data on temperature, pressure and humidity are necessary to compute the structure function parameter of temperature which can then be converted to sensible heat flux (Kite and Droogers, 2000). An important feature of the scintillation technique is that, although the measurement is along a path of a light beam, this is actually an estimate of sensible heat flux over an area because of the wide fetch (Meijninger and Bruin, 2000). The method therefore forms an intermediate scale between field (point measurement) and the large-area remote sensing estimates with no instrument calibration requirement.

4.0 Establishment of a Catchment Monitoring Network

The Potshini catchment monitoring network comprises of gauging structures and instruments, most of them automated, for measuring and monitoring stream flows, sediment load, runoff generated from runoff plots, shallow ground water table, volumetric soil moisture content, soil moisture wetting front, soil infiltration rates, crop transpiration rates and other meteorological parameters. The Potshini catchment monitoring network was established to fulfill a threefold mission aimed at:

- Monitoring the hydro-climatological regime of the Potshini catchment in an effort to achieve an in-depth understanding of the hydrological regime of the catchment and in an effort to investigate the hydrological impacts of adoption and adaptation of water use innovations in the Potshini catchment.
- Establish and enable a capacity to assess, monitor, and manage water and environmental resources in the Potshini catchment especially to the local community.
- Provide an opportunity for future and further research through the establishment of a catchment monitoring network with a potential for upscaling and integrating into other networks. This is not withstanding the important process of engaging the local community in the monitoring network, firstly, through establishing cordial relationship with the local leaders and the community at large and involving the community in the monitoring activities.

4.1 Climatic Parameters

Rainfall is one of the main parameters that drives the hydrological cycle in a catchment and hence the need to accurately estimate its occurrence, both spatially and temporal. Manual raingauges, if well managed, can provide relatively accurate daily rainfall data in a catchment and their affordability, availability and the ease to install and take readings makes them attractive especially to smallholder farmers. The fact that an individual has to take readings from a manual raingauge on a daily basis promotes the philosophy of participatory catchment monitoring to the Potshini community where some of the smallholder farmers are voluntarily recording daily rainfall from manual raingauges installed in their farms/homesteads. After a reconnaissance survey in the catchment, 8 potential sites were identified in the $1.2km^2$ Potshini catchment for installing manual raingauges, and which were homesteads in the Potshini community. The members of the identified homesteads were then approached, especially the head of the homestead, to seek permission to install the manual raingauges and most importantly their goodwill in taking daily rainfall readings. There is a cordial cooperation and participation from all homesteads so far approached and in each homestead, a person has been identified to be responsible for taking readings from the manual raingauge. Each manual raingauge is accompanied by a rainfall data recording booklet which is translated into the local language, the *IsiZulu*. The recording of rainfall is done twice a

day, i.e at 09h00 and 17h00, from which the daily average rainfall could be computed as the average of the morning and evening readings

The SSI programme has been collaborating with the ARC-Landcare project in Bergville district (Smith et al., 2004) in research and sharing of information and data has been one of the key attributes of such collaboration. This research study has continued to benefit and get access to the meteorological data from the ARC telemetric weather station which is located approximately 4km downstream of the Potshini community and close to one of the stream flow gauging structures, i.e the pressure transducer. Uploading of data from this weather station is on a daily basis, both hourly and daily data time steps. It is envisaged that another weather station will be set up at the Potshini catchment, in the midst of the community, before the end of August 2005 and which is expected to augment the downstream ARC weather station in depicting the spatial variation of weather parameters in the area.

4.2 Stream Flow Measurements

Stream flow at the Potshini catchment is monitored at two locations by use of an H-flume and a Pressure transducer coinciding with nested catchments of 1.2 and 10km^2 respectively. Voltage measurements of the pressure transducer are logged after every 5 minutes with a HOBO data logger and the acquisition of the stream flow data involves the translation of the output voltage signal of the pressure transducer into stream flow depths using a rating curve for that section. The H-flume has a discharge capacity of 3.34m^3/s and governed by a set of 3 rating equations, each describing a unique stage-discharge relationship for a given range of flow depth (Ackers et al., 1978) corresponding to high, low and intermediate flows. The design of the H-flume is described in detail in Kongo et al., (2005). The H-flume is also equipped with an ISCO sampler with a capacity of 24 sampling bottles and which is controlled by the MCS data logger. The sampling scheme has been programmed to take into account the variation of flow by taking frequent samples during a changing flow. This is due to the fact that water quality (e.g sediment load) will show less variation at constant flow and hence less frequent sampling is required at constant flow.

4.3 Runoff Plots

A standard runoff plot, as described by the Soil Conservation Services (SCS), measures 22.13 m long with an appropriate width of greater than 2m on a slope of 9%. Such a runoff plot is used in estimating the soil erodibilty factor in the Universal Soil Loss Equation-USLE (Wischmeier and Smith, 1978). However, the 9% slope is hardly achieved especially in agricultural fields, and hence the approach and focus in this study is on investigating hydrological processes within a runoff plot (a controlled micro catchment) and trying to compare such results from other runoff plots under different treatments but on similar slopes of less than 9%. This approach was adopted in designing the 11 runoff plots which were installed in the Potshini catchment, in an effort to investigate the influence and impact of conservation agriculture practices i.e water use innovations, on surface runoff generating characteristics in the predominantly agricultural catchment. The 11 runoff plots were designed while taking into account the rainfall intensities in the area. The dimensions of the runoff plots were 10m long and 2.45m wide and strips of 0.245m wide galvanized sheet metal was used to demarcate the area under each runoff plot. The knowledge of the rainfall intensity was useful in an effort to estimate the size of the tipping buckets, which are being used to measure surface runoff, and subsequent calibration of the tipping volumes.

4.4 Soil Moisture Profiling

The monitoring of the volumetric soil moisture in the Potshini catchment is being implemented by use of the Time Domain Reflectometry (TDR). The concept of TDR involves measuring the bulk electrical conductivity of the soil within a radius of 150mm and converting it into volumetric soil moisture content at any depth. This is facilitated by use of access tubes which are inserted into the soil profile to convenient depths. Several methods have been suggested on how to insert these access tubes into the soil and one of them is by pre-boring holes with appropriate soil augers, of relatively small diameter, and inserting the access tubes into the augered holes as was done in the Potshini catchment. A total of 16 access tubes of different lengths ranging from 1.2m to 1.5m have been inserted in various sites in the 1.2 km^2 Potshini catchment, most of them being in the runoff plots under different land management practices. A weekly regime for monitoring volumetric soil moisture in the Potshini catchment has been established, where readings have continued to be taken at different depths of 30cm interval in each access tube.

4.5 Shallow Observation Ground Water Wells

Through the collaboration and participation of the Potshini community, 14 shallow observation groundwater wells were installed in the Potshini catchment. Since the catchment is predominantly an agricultural area for smallholder farmers, following a reconnaissance survey, permission was sought from the local leaders and individual farmers to allow the augering of the 100mm holes in some of the farms on transects. The wells were strategically installed at sites where they could not interfere with the farming activities (at the edges or boundaries of farms), considering the fact that most of the farming operations in the area make use of animal and or tractor drawn implements. Two transects, one on each side of the catchment, were identified and running more or less perpendicular to the general slope of the catchment. The relatively shallow soils on one of the transects restricted the augering of the 2 wells to a depth of 2.4m while the rest were up to a depth of 3m. The basic approach was to auger the wells as

deep as possible to depths reaching the bedrock. Special 63mm diameter plastic pipes and of appropriate lengths were inserted into the augered wells such that at least 0.4m length of the pipe was above the ground surface. These special pipes have minute perforations at the bottom to a length of 0.6m. It is through such perforations that the shallow groundwater seeps into the pipe upon which the monitoring of fluctuation of the shallow groundwater table can be effected. To avoid clogging of the minute perforation by the fine clay soil at the bottom of the wells, a clean (washed) sand screen was packed around the plastic pipes covering the perforations to a height of 0.8m from the bottom of the wells. For each well, the rest of the well's depth was filled with the previously augered soil material save for the top 0.3m, where a cement motar was cast around the 63mm plastic pipe before a 0.4m x 0.4m concrete slab was cast at the top to a level slightly above the ground surface. Such cement and concrete works are to prevent any preferential flows from either side around the pipe when the soils are saturated during wet seasons.

4.5 Green Water Flows

A subset of cloud free 7-band satellite Landsat-ETM image (path 160, row 080) with a spatial resolution of 30m was used in estimating the actual evapotranspiration using SEBAL in this case study. The subset of the image, Figure 2, covered part of the Thukela river basin and the whole of the Potshini catchment. The acquisition date for this image was on 2nd March, 2001 and was freely downloaded from the Global Land Cover Facility (GLCF)-Earth Science Data Interface website. The fundamental idea in this satellite image processing exercise was to initiate a process - the spatial estimation of actual evapotranspiration using remote sensing techniques in the Thukela river basin and hence the date of acquisition of the satellite image was not of major concern. It is the expectation of this study to apply the SEBAL algorithm in real time situations and using the freely available NOAA/AVHRR images (with spatial resolution of 1.1 km) which has the advantage of almost daily scene coverage. In this case study, the 25 sub-models of the SEBAL algorithm were regrouped into 20 computational steps and which can broadly be classified into five general steps (Mohamed et al., 2004) as:

1) Pre-processing of the satellite image

This involved geometric and radiometric correction of the image and conversion of the digital numbers into spectral radiance and surface reflectance using the Plank's radiation equation. The relative distance between the earth and the sun in astronomical units was computed using the Allen et al., (1998) method.

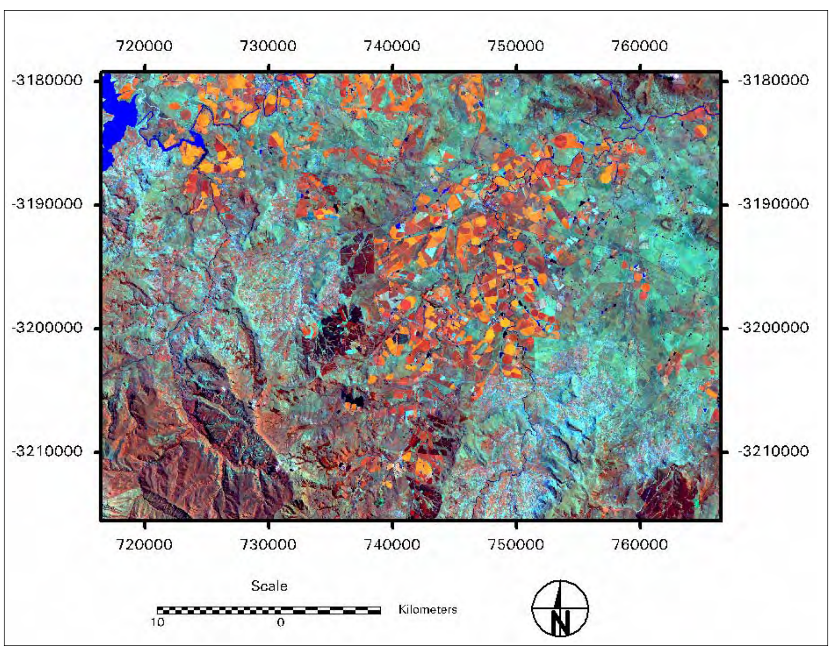

Figure 2. A subset of a Landsat7-ETM satellite image (path 160, row 080) used for estimation of actual evapotranspiration using SEBAL algorithm

The albedo adjusted for atmospheric transmissivity, i.e albedo at the top of the atmosphere was computed and further corrected to surface albedo using Zhong and Li (1988) and Allen et al., (1998) respectively.

2) Computation of the vegetation and atmosphere parameters

The Normalized Difference Vegetation Index (NDVI) for the image was calculated using the difference in reflection of radiance in red and near infra red region of the spectrum. For Landsat-7 images, the reflectance for bands 4 (NIR) and 3 (RED) are used to calculate NDVI. Calculation of the ratio of the thermal energy radiated by the earth's surface to the thermal energy radiated by black body at the same temperature, i.e, surface emissivity, was done using the relationship developed by Van de Griend and Owe (1993). It should be noted that this method is applicable in the range of NDVI=0.16-0.74 and values of surface emissivity should not be less than 0.9. The computation of the land surface temperature was based on correcting the effective satellite temperature at the capture of the image using the previously calculated surface emissivity.

3) Calculation of net radiation and soil heat flux

The net radiation was determined as the residual difference between the sum of incoming short and long wave radiation and the outgoing long wave radiation. The incoming short wave radiation was computed as a function of the solar incidence angle, relative earth-sun distance and the atmospheric transmissivity while the incoming long wave radiation was calculated based on the surface emissivity and observed air temperature as indicated in the Bastiaanssen et al., (1998a) method. The outgoing longwave radiation was computed as a function of surface temperature and surface emissivity using the Stefan-Boltzman equation. The soil heat flux was determined using a method derived by Bastiaanssen et al., (1998a) which relates the net radiation, surface temperature, surface albedo and NDVI to soil heat flux.

4) Determination of sensible heat flux through an iterative procedure

Sensible heat flux is the rate of heat loss to the air by convection and conduction, due to a temperature difference. In this case study, the sensible heat flux was computed using the heat transport approaches while taking into account aerodynamic resistance to heat transport. The initial stage involved calibrating the image temperature differences to the energy balance by deriving and using a linear relationship between a wet and dry pixel manually selected from the image. Sensible heat flux is a function of the temperature gradient, surface roughness and wind speed. It is thus difficult to compute due to the fact that temperature gradient and surface roughness are a function of each other and hence at any time there are two unknowns in this functional relationship. This was solved by iteration utilizing Monin–Obukhov similarity theory to correct for the buoyancy effects (Mohamed et al, 2004). The wind speed at the blending height derived from the ground measurements was used to estimate the surface roughness.

5) Computation of instantaneous latent heat flux and evaporative fraction

The instantaneous latent heat flux was computed using Equation 1 above as described by Bastiaanssen et al., (1998a) and an evaporative fraction (EF) for each pixel was calculated using Equation 2 by Bastiaanssen, (2000).

$$EF = \Lambda = \frac{LE}{R_n - G} = \frac{LE}{LE + H} = \frac{1}{1+\beta} \quad (2)$$

where β is the Bowen ratio (H/LE). Computation of evaporative fraction is the last step in the SEBAL algorithm from which other moisture indicators are derived from. The advantage of using the evaporative fraction over the Bowen ratio is that the former shows less variation during the daytime than Bowen ratio (Farah and Bastiaanssen, 2001; Mohamed et al., 2004) and is equal to its daily value integrated over a period of 24hours. The daily actual evapotranspiration can be estimated using Equation 3.

$$LE = \Lambda(R_{n24} - G) \quad (3)$$

where R_{n24} is the daily (24 hours) net radiation. For a day, the soil heat flux can be assumed negligible, as it balances out during the day and night, and hence the daily actual evapotranspiration (mm/day) for the entire image under this case study was calculated using Equation 4.

$$ET = [\Lambda(R_{n24}) / \lambda * \rho_w] 86400 * 10^3 \quad (4)$$

where λ is the latent heat of vaporization (J/kg) and ρ_w is the density of fresh water (kg/m^3). The root zone soil moisture content was empirically derived from the evaporative fraction using the Ahmed and Bastiaanssen (2003) method as shown in Equation 5, i.e:

$$\frac{\theta}{\theta_{sat}} = e^{(\Lambda - 1)/0.421} \tag{5}$$

where θ is the soil moisture content and θ_{sat} is the saturation soil moisture content.

5.0 Results and Discussion

Preliminary analysis of some of the data obtained from the Potshini catchment monitoring network is presented here.

5.1 Runoff Plots and Soil Moisture

Preliminary experimental results obtained from the 5 out of 11 runoff plots installed in the Potshini catchment are presented. Cumulative surface runoff data and volumetric soil moisture profile from 5 agricultural land use management practices, generally categorized as conventional and conservation agricultural practices, for the period between December 2004 and June 2005 is as shown in Figures 3 and 4 respectively. The general trend observed from Figure 3 is that, conservation tillage significantly reduces surface runoff volumes as compared to conventional tillage practices. Cumulative surface runoff generated under conventional tillage amounted to over 1240 litres as compared to 1130, 810, 420, 250 litres under different conservation tillage practices. Mulch was not applied in the initial stage of this study for the purpose of progressive comparative analysis in the subsequent seasons under mulching. At the moment, all the experimental sites are under grazing; where livestock in the community is freely grazing on the plots, save for those where the influence of mulching is being investigated.

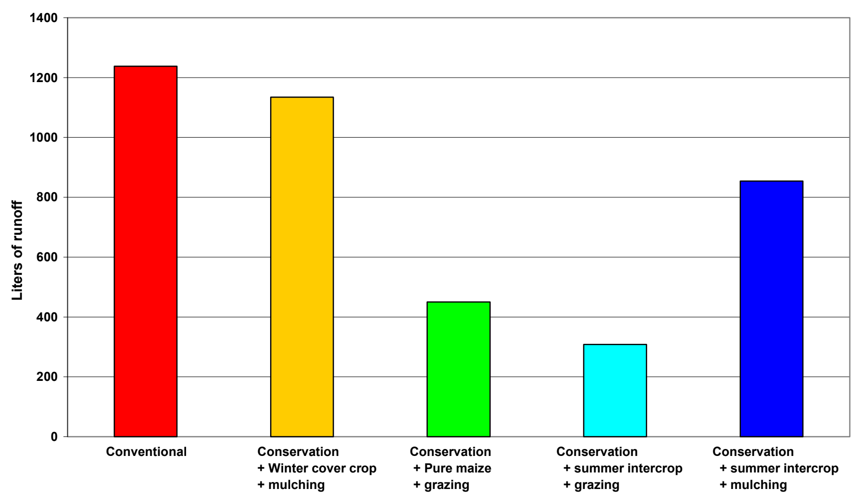

Figure 3. Comparison of cumulative surface runoff generated under different agricultural land management practices in Potshini

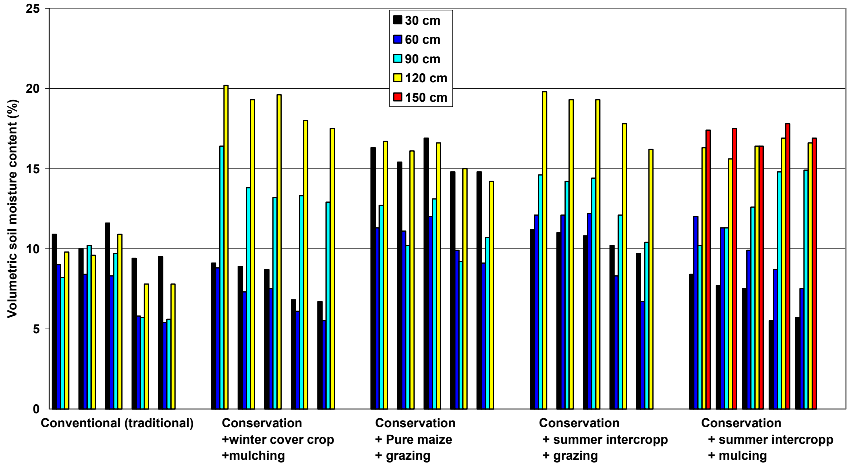

Figure 4. Volumetric soil moisture content profile under different agricultural land management practices in Potshini: dates- April (21st, 28th,) May (5th, 13th, 18th)

Due to instrumentation problems, the duration of soil moisture profile data considered in this case study was from April 2005 onwards, i.e towards the end of the wet season, with focus in the investigation of the influence of the innovative agricultural land management practices to the soil moisture content during dry spells. The volumetric soil moisture data taken at different soil depths and dates under different agricultural land management practices (treatments) is shown in Figure 4. The general trend depicted in Figure 4 is that the volumetric soil moisture content in all treatments and at all depths is declining due to the influence of the dry season. From Figure 4, one can observe the emerging pattern of more soil moisture being retained under conservation tillage practices compared to conventional tillage, especially at depths greater than 120cm. This could indicate that conservation tillage practices may have an influence to the occurrence of shallow groundwater in the Potshini catchment. This is yet to be investigated under this ongoing study.

5.2 SEBAL Results

On application of the SEBAL algorithm, two maps were generated, i.e. the day's spatial variation of actual evapotranspiration (Figure 5) and relative root zone soil moisture (Figure 6) over the entire subset image for 2nd March 2001. Relatively high actual evapotranspiration rates are observed to have taken place in areas under active growing crops as seen from Figures 2 and 5. It was also observed that the same areas had relatively high NDVI values indicating high vigour of vegetation/crop growth. A comparison was done for this day between SEBAL estimates for actual evapotranspiration and from a weather station in Bergville, on the same pixel. It was found out that SEBAL over estimated actual evapotranspiration by 1.3mm, with the weather station reading being 7.2mm. It was not possible to verify estimates of relative root zone soil moisture in this case study due to lack of appropriate data. Nevertheless, SEBAL estimates of relative root zone soil moisture have been verified with measured data in other regions (Ahmed and Bastiaanssen, 2003) and have been found to compare well. Further investigation and verification of these output form an important part of the next two years investigation.

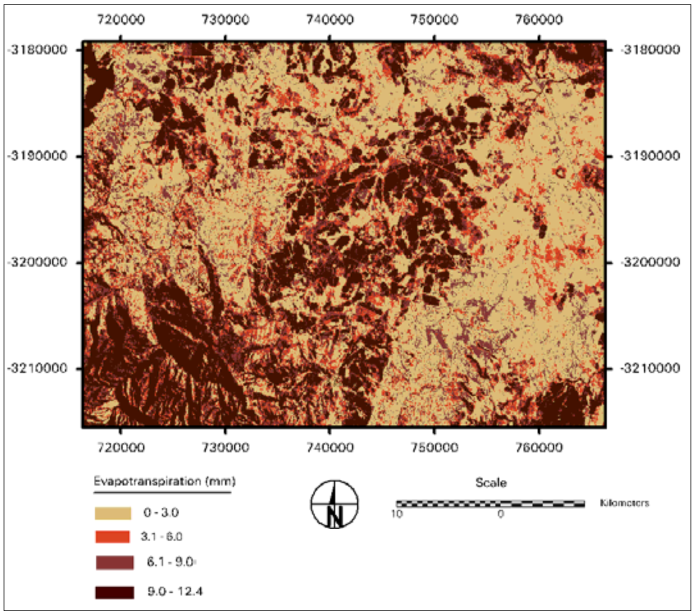

Figure 5. Spatial variation of estimated actual evapotranspiration in the Potshini catchment and surrounding areas for 2nd March 2001 computed using the SEBAL algorithm

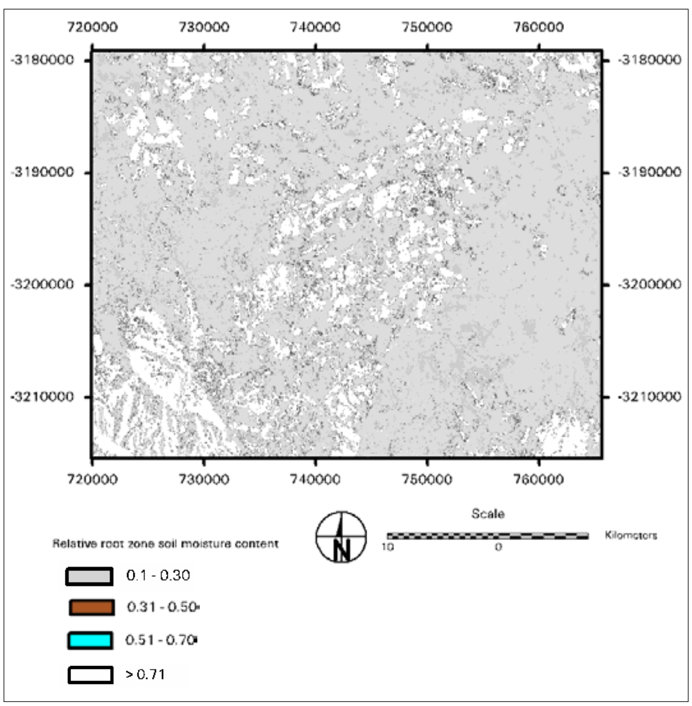

Figure 6. Spatial variation of relative root soil moisture in the Potshini catchment and surrounding areas for 2nd March 2001 computed using the SEBAL algorithm

6.0 Conclusion

A catchment monitoring network has been established at the Pothini catchment and the SEBAL algorithm was used to derive actual evapotranspiration and relative root zone soil moisture from a Landsat7-ETM satellite image. Preliminary results on the impact of innovative agricultural practices on the field soil-water balance indicate that such practices can reduce surface runoff and increase soil moisture content. The relatively small difference observed between estimates of actual evapotranspiration from weather station data and SEBAL, and given the fact that SEBAL was applied for a single day, indicates the potential of using SEBAL in the Potshini catchment and Thukela river basin (large spatial scales) especially in quantifying actual water use by crops/vegetation, e.g forestry in line with the 1998 National Water Act in an effort to manage the river basin's water resources in a sustainable way.

Reference

Ackers, W.R., White, J.A., Perkins, Harrison, A.J., 1978. Weirs and flumes for flow measurement

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. Crop evapotranspiraton, FAO Irrigation and drainage paper, FAO 56, FAO

Bastiaanssen, W. G. M., Menenti, M., Feddes, R. A., Holtslag, A.A.M. 1998a. A remote sensing Surface Energy Balance Algorithm for Land (SEBAL), Part 1: Formulation, Journal of Hydrology 212-213: 198-212.

Bastiaanssen, W.G.M., Pelgrum, H., Wang, J., Ma, Y., Moreno, J., Roerink, G.J., van der Wal, T. 1998b. The Surface Energy Balance Algorithm for Land (SEBAL), Part 2: Validation, Journal of Hydrology 212-213: 213-229.

Bastiaanssen, W. G. M. 2000. SEBAL-Based Sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey, Journal of Hydrology 229: 87-100.

Bastiaanssen, W.G.M., Ud-din-Ahmed, M., Chemin, Y. 2002. Satellite surveillance of evaporative depletion across the Indus Basin. Water Resources Research. 38 (12), 1273–1282.

BEEH, 2003. Thukela catchment, basin initiative submitted by the School of Bioresources Engineering and Environmental Hydrology of the University of KwaZulu-Natal to the UNESCO-Hydrology for Environment, Life and Policy (HELP)

Cain, J.D., Rosier, P.T.W., Meijninger, W., De Bruin, H.A.R. 2001. Spatially averaged sensible heat fluxes measured over barley, Agricultural and Forest Meteorology, Vol. 107, 307-322

Duffie, J.A., Beckman, W.A. 1991. Solar engineering of thermal processes, 2nd edition. John Wiley and Sons, New York

Falkenmark, M. 1995. Land-water linkages - A synopsis. in Land and Water integration and river basin management. FAO Land and Water Bulletin No 1 : 15-16. FAO, Rome, Italy.

Farah, H.O., Bastiaanssen, W.M.G. 2001. Impact of spatial variation of land surface parameters on a regional evaporation: a case study with remote sensing data. Hydrological Processes. 15(9), 1585-1607

GHARP. 2002. Evaluation of rainwater harvesting systems: Towards adaptive strategies for food security in Greater Horn of Africa. Greater Horn of Africa Rainwater Partnership (GHARP), Draft Case Study Reports. Kenya Rainwater Association, Nairobi, Kenya.

van der Griend, A.A., Owe, M. 1993. On the relationship between thermal emissivity and the normalized difference vegetation index of natural surfaces. Int. J. Remote Sensing 14 (6), 119–131.

Jewitt, G.P.W., Gorgens, A.H.M. 2000. Scale and model interfaces in the context of integrated water resources management for the rivers of Kruger National Park; Water Research Commission Report No. 627/1/00

Kite, G.W., Droogers, P. 2000. Comparing evapotranspiration estimates from satellites, hydrological models and field data; Journal of Hydrology 229, 3-18

Kongo, V.M., Jewitt, G.W.P, Lorentz, S. 2005. Establishment of a catchment monitoring network through a participatory approach in the Potshini catchment in Thukela river basin. Draft Manual. Smallholder System Innovations (SSI) research programme. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, S.Africa.

Meijninger, W.M.L., Bruin, H.R.A. 2000. The sensible heat fluxes over irrigated areas in western Turkey determined with large aperture scintillometer, Journal of Hydrology Vol. 229, pp 42-49

Mohamed, Y.A., Bastiaanssen, W.G.M., Savenije, H.H.G. 2004. Spatial variability of evaporation and moisture storage in the swamps of the upper Nile studied by remote sensing techniques. Journal of Hydrology 289 (2004) 145–164

Pandey, D.N., Anil, K.G., David, M.A. 2003. Rainwater harvesting as an adaptation to climate change, Current science, Vol. 85, No. 1,10

Rockström, J. 1999. On-farm green water estimates as a tool for increased food production in water scarce regions. Phys. Chem. Earth (B), 24(4): 375-383

Rockström, J., Kitalyi, A., Mwalley, P. 1999. Conservation tillage and integrated land management: Field experiences and extension approaches. Paper presented at the ATNESA/SANAT International Workshop on Empowering Farmers through Animal Traction into the 21st Century. South Africa, September 20-24, 1999.

Rockström, J. 2000. Water resources Management in smallholder farms in eastern and Southern Africa: an overview, Phys. Chem. Earth (B), Vol 25(3), 275 – 283

Rockström, J., Barron, J., Fox, P. 2001. Water productivity in rainfed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agro-systems. Paper presented at an IWMI Workshop on Water Productivity in Agriculture. Colombo, Sri Lanka. November 12-14, 2001.

Savenije, HHG. 1999. The role of green water in food production in Sub-Saharan Africa. Article prepared for FAO. *http://www.fao.org/ag/agl/aglw/webpub/greenwat.htm* [accessed on 15th July 2004]

Smith, H.J., Trytsman, G., Bloem, J.F., Everson, T., Mthethwa, S. 2004. Development and implementation of sustainable land management practices in the Bergville district of the KwaZulu-Natal Province. Fourth progress report, Bergville/Emmaus Landcare project 2003/2004

SSSA. 1987. Glossary of Soil Science Terms. Soil Science Society of America, Madison, WI, USA

Tasumi M., Richard,T., Richard, G.A., James, L.W. 2003. US validation tests on the SEBAL model for evapotranspiration via satellite, ICID workshop on remote sensing of evapotranspiration for large regions, 17th September 2003.

Wischmeier, W.H., Smith, D.D. 1978. Predicting rainfall erosion losses-A guide to conservation planning. Washington DC. US Depatment of Agriculture. Agriculture handbook No. 537

Zhong, Q., Li, Y.H. 1988. Satellite observation of surface albedo over the Qinghai-Xizang plateau region. Advanced Atmospheric Science. 5, 57-65